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Monitoring River Ice Break-Up from Space

Ice-covered reaches of the Ottawa River were observed from the NOAA-4 polar orbiting satellite and the GOES-1 geostationary satellite.

Abstract: *Visible images from operational environmental satellites provide an effective means to assess formation and dissipation of river ice. The National Environmental Satellite Service (NESS) receives 1-km resolution images daily from polar-orbiting NOAA satellites and every 30 minutes during daylight from NOAA geostationary satellites. During the period April 4-14, 1976, fourteen ice-covered reaches on the Ottawa River between Lake Timiskaming and Montreal were monitored daily by using imagery from NOAA-4 and GOES-1 satellites. The ice-covered reaches were observed to break up in place; at the end of the 10-day study period only three of the original 14 remained.*

Satellite views of the river permitted the measurement of changes in the length of the individual ice-covered reaches. High-resolution imagery from NASA's Landsat satellites as well as digital tape data from the NOAA polar-orbiting satellites were used to calibrate the measurements from the operational imagery.

Introduction

The dynamics of river ice is much studied because of the problems the ice creates with hydropower stations, bridge piers, and ship navigation. Environmental satellites deliver daily, even half-hourly, views of Earth and make possible the monitoring of ice growth, decay, and movement on the larger rivers. Observing the break-up of ice on the Ottawa River in 1976 from the NOAA-4 and GOES-1 satellites provided an opportunity to assess the usefulness (and limitations) of satellites for monitoring river ice.

The formation and break-up of river ice has been the subject of much research. An excellent literature review of the subject is provided by the U.S. Army Corps of Engineers, Lake Survey District (Bolsenga, 1968). Much of the literature is of Soviet origin, which is not surprising when one considers the chronic problem to navigation posed by river ice cover in the Arctic basin. Unfortunately, little work has been done on the application of remote-sensing methods to the study of river ice. One exception is the study by Mashukov (1957), in which ice bridges and dams on the Syr Danya River were studied by means of aerial reconnaissance over a seven-year period. Further, good agreement was obtained by Molchanov and Vlasov (1974) by using aerial photography to determine the longitudinal profile of a river surface in an ice jam sector. A unique advantage of remote-sensing techniques was advanced by Golek (1957) who stated that one of the pitfalls in empirical methods of ice jam forecasting was "the lack of observations for the entire length of the river course." Such full-length views are

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provided in satellite images as demonstrated in this paper.

Ottawa River Basin

The Ottawa River drains an area of approximately 146,000 km² and includes portions of the provinces of Ontario and Quebec. The Ottawa River falls more than 325 m in only 1100 km, making the river a good source for hydroelectric power and providing most of the electricity used by the 1,000,000 people living within the basin. In fact, the numerous dams on the river restrict commercial navigation to the segment between the city of Ottawa and the Ottawa River estuary at Montreal.

The climate of the basin is more continental than maritime, resulting in long, cold winters. The length of the ice season varies substantially from year to year; ice formation usually begins during November and the river becomes totally frozen by the end of December. As found by Deslauriers (1965) in his studies of the Chaudiere River in Quebec, break-up generally begins at rapids and points of major inflow, then progresses to less dynamic segments of the river. An examination of historical records for the Ottawa River shows that this break-up process usually begins in March and lasts about 20 days, but the date of total break-up has occurred as late as May 20.

Satellite Sensors and Imagery

Satellite images were acquired by two polar orbiting satellites, NOAA-4 and Landsat-2, and from one geostationary satellite, GOES-1. The NOAA-4 and GOES-1 satellites are operational, viewing the study area at least once daily; the Landsat-2 satellite is used primarily for research, providing coverage only once every 18 days.

The NOAA-type satellites scan Earth in 25 orbits every two days at an altitude of approximately 1500 km in a sun-synchronous, near-polar orbit. The orbital track is essentially the same every other day, although the orbit of the satellite progresses eastward at one degree of longitude every 25 orbits. Of the sensors on board the spacecraft, the Very High Resolution Radiometer (VHRR) provides the most useful data for river ice monitoring. This instrument scans Earth in both visible (0.5-0.7μm) and thermal (10.5-12.5μm) regions of the spectrum at a resolution of 1 km (Schwalb, 1972). Most of the panoramic distortion of standard images resulting from satellite orbital motion, Earth rotation, scanning by the VHRR perpendicular to orbital motion, and the Earth's curvature can be removed through computer processing.

The Geostationary Operational Environmental Satellites (GOES) are placed in orbit 35,800 km above the equator at an eastward speed of 11,000 km/hr, which keeps the spacecraft fixed over a point on the equator. GOES-1 is located at 75°W longitude. The Visible and Infrared Spin-Scan Radiometer (VISSR) of GOES-1 produces visible (1-km resolution) and thermal (8-km resolution) images as frequently as every 30 minutes. The visible detector of the VISSR responds to the portion of the spectrum between 0.55 and 0.75 μm; the thermal detector responds to the portion between 10.5 and 12.5 μm. The distortion in VISSR imagery increases with distance away from the equator, thus impairing the usefulness of GOES for monitoring river ice. However, useful imagery can be obtained at latitudes as high as 50°.

Orbiting the Earth at 900 km in a near-polar sun-synchronous orbit, Landsats 1 and 2 deliver 80-meter resolution from the Multispectral Scanner Subsystem (MSS) in four different wavelength bands: 0.5-0.6 μm, 0.6-0.7 μm, 0.7-0.8 μm, and 0.8-1.1 μm. The area covered by an individual frame is 185 km square (G.E. Corp., 1972). Landsat images are almost distortion-free and provide excellent details of surface features.

Procedure

VHRR images received from the NOAA-4 satellite by the National Environmental Satellite Service (NESS) Command and Data Acquisition Station at Wallops Island, Virginia, were transmitted over telephone landlines to NESS Headquarters in Suitland, Maryland, where the 1:10,000,000 scale images were developed. Thus, the authors had the images in hand within hours of a satellite pass. These standard images were magnified and rectified to overlay a 1:2,225,000 scale basin map through use of an optical transfer device, the Zoom Transfer Scope (ZTS). Rectification on the ZTS can be accomplished by use of an anamorphic stretch control which permits enlarging the image up to twice its original size in any linear direction (Theis, 1976). Since the NOAA-4 satellite always passed over the subject area in a near north-to-south path, the attendant panoramic distortion could be eliminated by stretching the image in an east-west direction. Final registration of image and map on the ZTS was done by locating and overlaying prominent landmarks such as lakes, rivers, and shorelines. After registration, the ice-covered river segments were delineated on the basin map. A simple, mechanical map-measuring device was then used to determine the length, in kilometers, of each ice-covered segment of the river. Once the imagery was in hand, the entire procedure usually was completed in 30 minutes.

Unlike the NOAA-4 VHRR data, the data stream from GOES-1 was received directly at NESS headquarters in Suitland; no land-line transmission was necessary. Thus, the VISSR images from GOES-1 were made available to the authors in near real-time. The method of analysis was almost identical to that for the VHRR images except that the VISSR images are rectified on the ZTS by stretching in the direction from the study area to the satellite's subpoint (in this case north-south).

Operational Imagery Analysis

LOCATION OF RIVER ICE

Following the procedure outlined above, 14 distinct ice-covered reaches on the Ottawa River were located and identified on the NOAA-4 VHRR image of April 5, 1976. The ice-covered reaches were successively labeled beginning at Lake Timiskaming (*A*) and progressing downstream to Montreal (*N*). The portion of the Ottawa River above Lake Timiskaming, being dominated by several large reservoirs (Lac Quinze, Lake Simard, Lac Decelles, Dozois, and Cobonga), was omitted from this study. Figure 1 is a map of the basin with the labeled ice-covered reaches indicated in black. Figure 2 is a portion of the rectified NOAA-4 frame from which the map was derived. All the ice-covered segments can be seen on the image except for *A*, which was obscured by satellite transmission noise. An ice-free reach of the Ottawa River on Figure 2 can be seen in forest-free, snow-covered terrain between *I* and *J*.

Ice jam formation may sometimes be caused by sharp curves in a river channel or bifurcation of the main channel by an island (Laszloffy, 1948). Other causes of persistent ice cover include cold weather, an extended stretch of dead water, or manmade obstacles such as dams (Deslauriers, 1965). Deep water in the middle of a river combined with a small slope of the river bottom can cause persistance of ice-cover in downstream reaches (Kravchenko, 1959). The presence of ice in all 14 reaches labeled in Figures 1 and

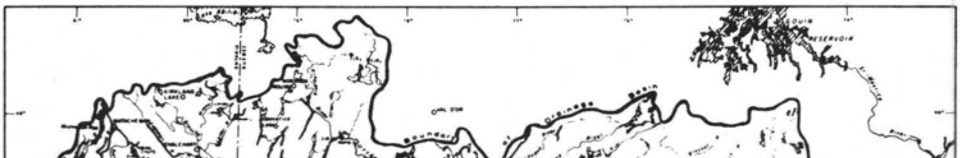

FIG. 1. Map of Ottawa River drainage basin with ice covered reaches (*A-N*) delineated in black.

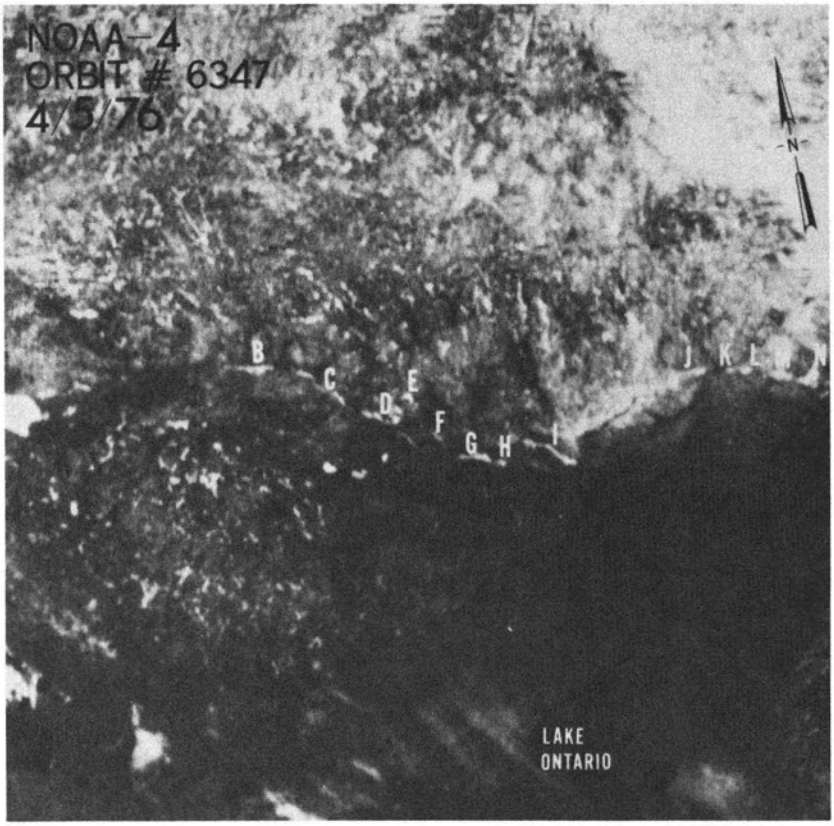

FIG. 2. Portion of NOAA-4 image (computer enhanced and enlarged) form 4/5/76 covering Ottawa River basin with annotated ice reaches.

2 can be attributed to at least one and sometimes combinations of the aforementioned conditions. For instance, cold weather can partially account for the persistence of ice in Lake Timiskaming, which is 2 degrees of latitude farther north than Montreal. Dams at Des Joachims, Sullivan Island, Chenaux, and Carillon may be responsible for ice-covered segments *G, E, F,* and *L,* respectively. Sharp river bends at Arnprior and Brittania may be responsible for ice-covered reaches *H* and *I*. Bifurcation of the river by Alumette Island may account for ice at *C* and *D*, and ice-covered segments *E* and *F* likewise may be attributed to Calumet Island. The profusion of ice-covered reaches in the downstream portion of the river (*J, K, L, M, N*) may be caused by the reduced slope of the river bottom in that area. In contrast, the presence of rapids (Mountain, Erables, LaCave, Johnson, Deux Rivieres, and Rocher Capitaine Rapids) may explain the large ice-free stretch between *A* and *B* (115 km). Table 1 provides a list of the ice-covered reaches, locations, and likely reasons for the presence of ice.

MONITORING OF BREAKUP

Ice in the Ottawa River was monitored over a 12-day period between April 3 and April 14, 1976. During this period clouds totally obscured the basin on five days, with all ice areas unobscured on four other days. At the end of the period only three of the original ice reaches remained: one was reduced to half its original size (*B*), and the other two were broken up into smaller pieces (*A* and *J*). The day-by-day sequence is given in Table 2. Computer-enhanced NOAA/VHRR imagery was available for April 5 and 7. Standard VHRR imagery was used for all other dates except on April 3 and 4 when clouds obscured the area. For these two dates, GOES-1 VISSR imagery was used instead. Figures 3a and 3b taken by the VISSR (April 4 and 14, respectively) graphically depict the ten-day reduction in the ice cover.

Deslauriers (1965) found that disappear-

TABLE 1. ICE REACHES ON THE OTTAWA RIVER, THEIR LOCATION AND POSSIBLE CAUSES FOR THEIR PERSISTENCE.

Reach	Approx. Location Determined from Satellite Imagery	Possible Reason for Persistence of Ice Cover
A	Lake Timiskaming	High Latitude, slack water, dam at Timiskaming Station.
B	Above Des Joachims Power Station	Slack water, bifurcation of channel by an island, dams at Des Joachims.
C	Above Allumette Island	Lack of tributaries, bifurcation of channel caused by Allumette Island.
D	Branch of River south of Allumette Island	Constriction of channel by Allumette Island, river bend.
E	Above Calumet Island	Bifurcation of channel caused by Calumet Island, river bend, Sullivan Island Control Dam.
F	Above Chenaux Power Station	Constriction of channel by Calumet Island, dam at Chenaux, river bend.
G	Above confluence of Ottawa R. and Madawaska River	River bend.
H	Above confluence of Ottawa R. and Mississippi River	River bend.
I	Above Brittannia	River bend, lack of tributaries.
J	Above confluence of Maskinong and Ottawa River	Small slope (downstream reach).
K	Near Hawkesbury Gauging Station	Small slope (downstream reach).
L	Above Carillon Power Development and Gauging Station	Carillon Dam, small slope (downstream reach).
M	Below Carillon Power Development and Gauging Station	Small slope (downstream reach).
N	At mouth of River (above Montreal)	Small slope (downstream reach).

ance of ice on the nearby Chaudiere River in southwest Quebec was usually the result of hydraulic transport rather than melting. Just the opposite was found in this study of the Ottawa River; the ice-covered reaches appeared to break up and melt in place. The Ottawa River break-up was similar, however, in one respect to the Chaudiere River break-up as reported by Deslauriers (1965): the break-ups of the tributaries were generally earlier than those of the main river.

LANDSAT IMAGERY ANALYSIS

The excellent quality of Landsat limited-area MSS imagery was described earlier. Figure 4 vividly portrays these two attributes. Both scenes in Figure 4 cover exactly the same area: the top scene is from Landsat MSS band 5 (0.6-0.7 μm) while the bottom scene is from NOAA-4 VHRR (visible); both were taken on April 5, 1976. Whereas the Landsat image is sharp, with the boundaries of the numerous frozen lakes easily defined, the NOAA VHRR images appears blurred—a result of the almost 12 times enlargement necessary to obtain the same scale as that of the Landsat MSS. Many of the lakes seen in the Landsat image are smaller than 1 km and are thus not apparent in the VHRR image. The "blockiness" of the individual pixel elements of the VHRR is noticeable.

The difference in resolution between the VHRR image and the MSS image in Figure 4 is dramatically apparent at the downstream edge of the ice-covered reach *B*. On the MSS image, the leading edge of the ice is seen to be blocked by an island in the main river channel. (The ice actually is blocked by dams on the northern and southern sides of the island.) This island is simply too small to be resolved in the VHRR image. Another Landsat image, taken on April 7, revealed an ice-covered reach on the segment of the river east of Calumet Island. The ice probably persisted in this reach because of narrowing of the channel and was prevented from moving downstream by the presence of Bryson Dam. Owing to the narrowness of this reach of the river, the ice was never detected on either the VHRR or VISSR imagery of the same date. In another case, ice-covered reaches (*A* and *D*) observed on the VHRR imagery were seen to be composed of two or three separate segments on the corresponding Landsat image. Conversely, two separate ice-covered reaches (*G* and *H*) were

TABLE 2. LENGTH OF INDIVIDUAL ICE SEGMENTS IN OTTAWA RIVER FROM SATELLITE ANALYSIS.

Imagery Used	4/3/76 VISSR GOES-1	4/4/76 VISSR GOES-1	4/5/76 Enhanced VHRR NOAA-4	4/7/76 Enhanced VHRR NOAA-4	4/8/76 VHRR NOAA-4	4/9/76 VHRR NOAA-4	4/10/76 VHRR NOAA-4	4/14/76 VHRR NOAA-4
ICE REACH	LENGTH OF ICE SEGMENT, Km							
A	87	87	82	CLOUDY	A1* 62 A2* 17	CLOUDY	CLOUDY	A11* 28 A12* 28 A2* 17
B	21	19	21	19	17	11	11	11
C	38	33	35	C1* 11 C2* 24	C1* 11 C21* 5 C22* 9	C1* 9 C21* 0 C22* 12	C1* 9 C21* 5 C22* 11	0
D	CLOUDY	33	29	D1* 16 D2* 14	D1* 14 D2* 10	D1* 11 D2* 9	D1* 7 D21* 3 D22* 3	0
E	CLOUDY	7	7	7	7	7	7	0
F	CLOUDY	9	9	9	7	0	0	0
G	CLOUDY	19	19	17	15	7	5	0
H	CLOUDY	7	7	7	7	7	7	7
I	CLOUDY	35	31	28	28	I1* 7 I2* 7 I3* 12	I1* 7 I2* 7 I3* 9	0
J	CLOUDY	31	29	17	12	J1* 5 J2* 7	J1* 5 J2* 9	J1* 5 J2* 9
K	CLOUDY	7	5	0	0	0	0	0
L	CLOUDY	7	7	7	7	7	7	0
M	CLOUDY	14	16	M1* 7 M2* 7	M1* 7 M2* 7	M1* 7 M2* 7	M1* 5 M2* 5	0
N	CLOUDY	11	14	14	11	7	7	0
TOTALS	NA	319	318	NA	253	NA	NA	98
% of River Ice Covered	NA	55	55	NA	43	NA	NA	17

* Notations in the Table are as follows: If an ice segment, A for instance, broke into two pieces, they were named A1 and A2. If A1 subsequently broke into two pieces, they were A11 and A12.

actually found to be joined by a narrow channel of ice not discernible on the VHRR image.

Another advantage of the Landsat MSS is the ability to view the same area simultaneously in four different regions of the spectrum. In Figure 5 are MSS band 5 (0.6-0.7 μm) at top and MSS band 7 (0.8-1.1 μm) at bottom, respectively. The area pictured is the last 150 km of the Ottawa River as it empties into the St. Lawrence River. Note that the St. Lawrence River is essentially ice-free. However, the Ottawa River as viewed in the MSS band 5 image is ice- (and likely snow-) covered and it is rather difficult to distinguish from the surrounding snow-covered terrain. A dramatic difference is seen in the MSS band 7 (bottom) image; the Ottawa River here is easily discerned as a dark sinuous path cutting through the snow-covered region. Several studies (Strong et al., 1971; Wiesnet, McGinnis, and McMillan, 1975; O'Brien and Munis, 1975) have shown that it is often possible to detect

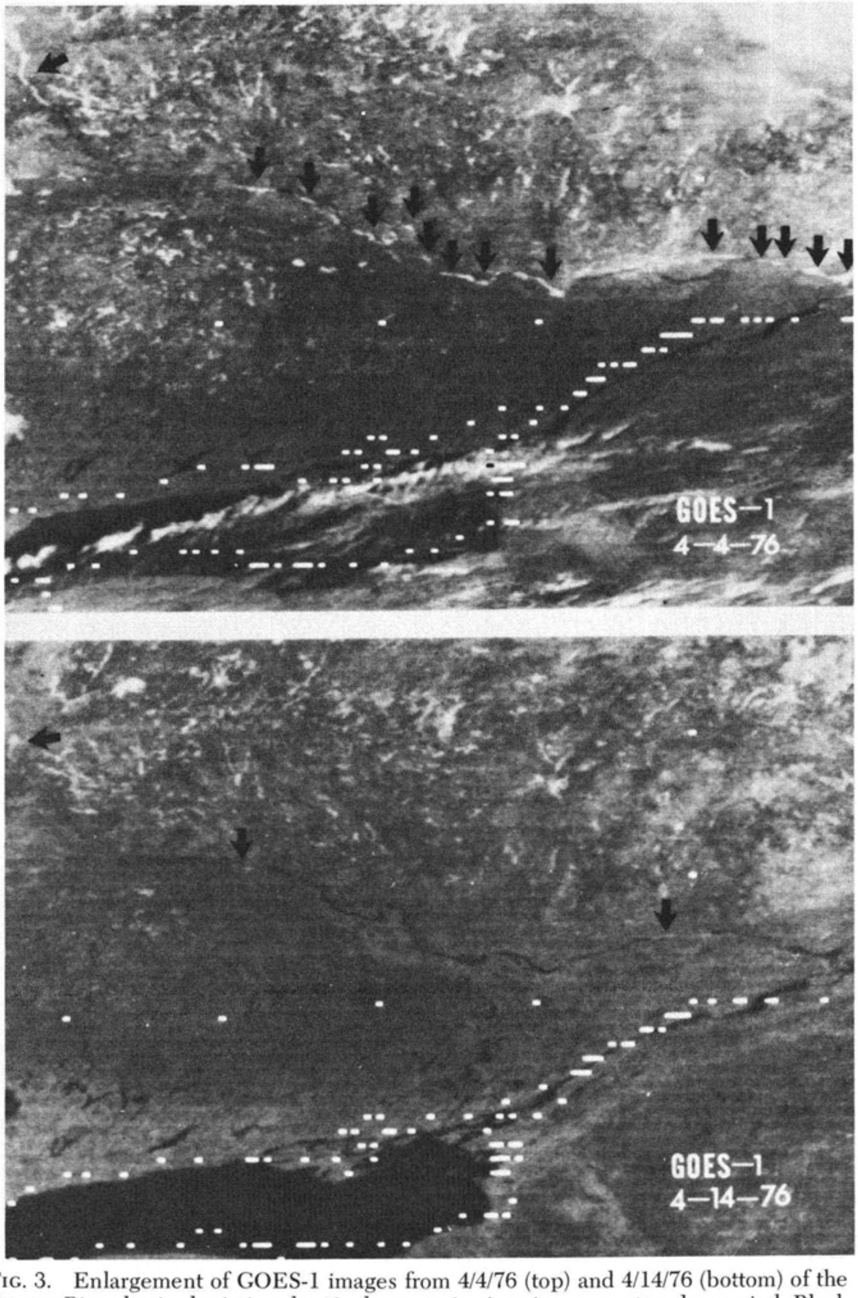

FIG. 3. Enlargement of GOES-1 images from 4/4/76 (top) and 4/14/76 (bottom) of the Ottawa River basin depicting drastic decrease in river ice over a ten-day period. Black arrows indicate ice covered reaches.

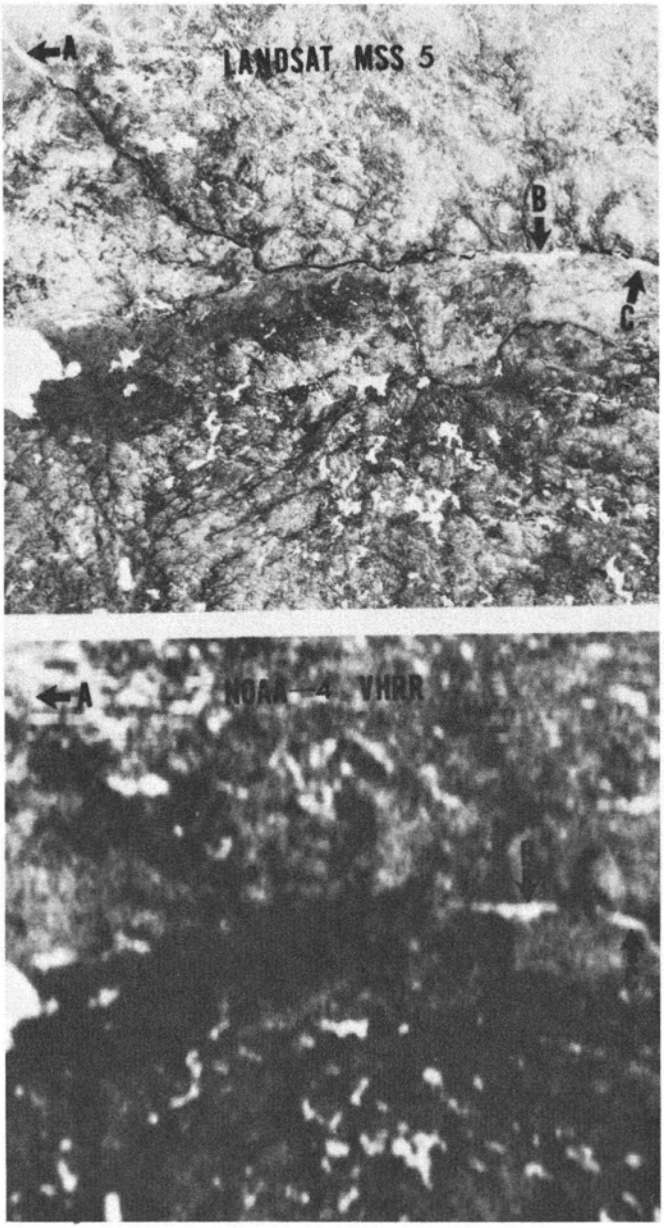

FIG. 4. Comparison of Landsat-2 MSS band 5 and NOAA-4 VHRR visible images, at same scale, viewing the western part of the Ottawa river basin, 4/5/76. Images were obtained within approximately one hour of one another.

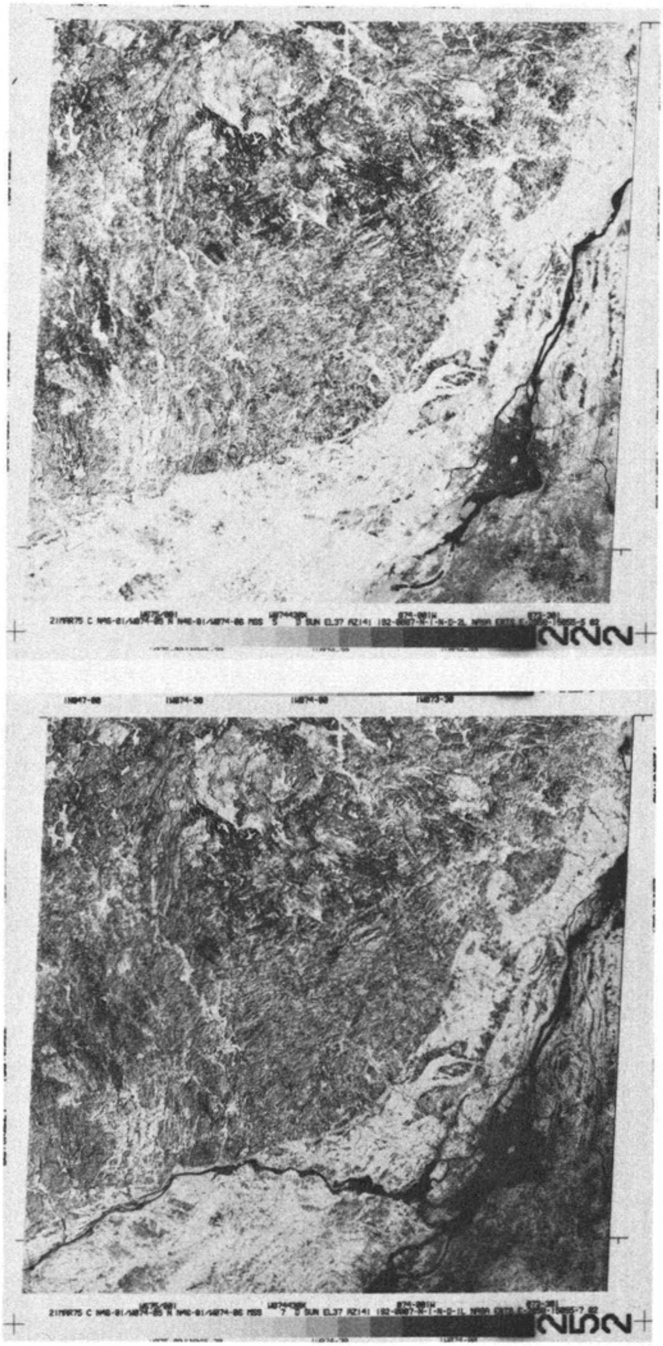

FIG. 5. Landsat-2 MSS band 5 (top) and MSS band 7 (bottom) views of Ottawa river estuary (1505 GMT, 3/21/75) showing decreased reflectance of metamorphosed snow and ice in the near-infrared.

metamorphosed or melting snow and ice by comparisons of simultaneous visible (MSS band 5) and near-infrared (MSS band 7) images. These studies indicate that the reflectance of snow and ice is less in the near-IR than in the visible portions at the spectrum. Furthermore, the reflectance of metamorphosed or melting snow and ice is less in the near-IR than fresh, non-melting snow. Thus, in this case, the ice on the Ottawa River is likely metamorphosed and may be in the initial stages of melt, since shelter temperatures were near −2°C at the time of satellite overpass.

Digital Analysis

Satellite data are recorded on digital tapes which permit processing the data in many ways. The VHRR visible channel is capable of discriminating 256 different levels of brightness, or energy levels. These energy levels can be arranged and displayed by assigning letters, numbers, and symbols to each of the levels. One example of such a display is presented in Figure 6. The area shown is almost identical to that of Figure 2. A threshold level which appears to best separate the snow-covered areas from snow-free terrain was chosen arbitrarily. Snow was represented by blanks, non-snow by M's. The use of M's and blanks is by no means completely accurate, for the snow-covered coniferous forest north of the Ottawa River is not represented by blanks. Rather, the numerous lakes, ponds, and clearings appear as blanks while the lesser reflectance of the dense coniferous vegetation is below the chosen threshold and, thus, retains the M designation. Even so, this simple technique does display the ice-covered reaches along the Ottawa River adequately.

To provide a more understandable display of the ice in the Ottawa River than is possible with black-and-white images, we employed an interactive system called the Man-Machine Interactive Processing Systems (MMIPS), which permits a thermatic approach for identifying various hydrologic features viewed by satellites. The MMIPS ingests specially formated tapes and, through the use of approximately 30 commands available to a keyboard operator, the system may be programmed to display the taped satellite data in color on a cathode ray tube (CRT). The system contains an adjustable color table limited to 64 steps which may be matched to any 64 sequential subranges of the 256 energy levels available for the VHRR data. The operator can rapidly search for the color table that best enhances the desired theme and then preserve the resulting image by photographing the CRT screen.

One color rendition of the Ottawa River ice photographed from the MMIPS CRT is shown in Plate 1 (NOAA-4, orbit 6347, 4/5/76). The data in Plate 1 have been averaged to produce a 2-km resolution image. Here the colors selected display the snow-free mixed forests northeast of Lake Ontario (and generally south of the Ottawa River) as dark green (*A*), while the snow-covered forests east of Lake Ontario (Tughill Plateau and the Adirondacks), north of the Ottawa River, and northwest of Lake Ontario as light green (*B*). The river ice and snow-covered forest clearings north of the Ottawa River are white (*C*), while unfrozen Lake Ontario and St. Lawrence River appear light blue (*D*). Clouds located in the right corner

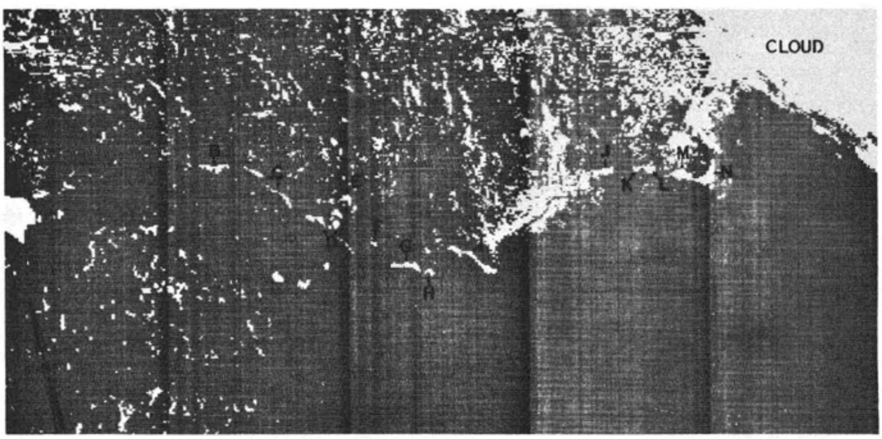

Fig. 6. Computer printout of Ottawa River basin from NOAA-4 VHRR data of 4/5/76 with ice covered reaches annotated.

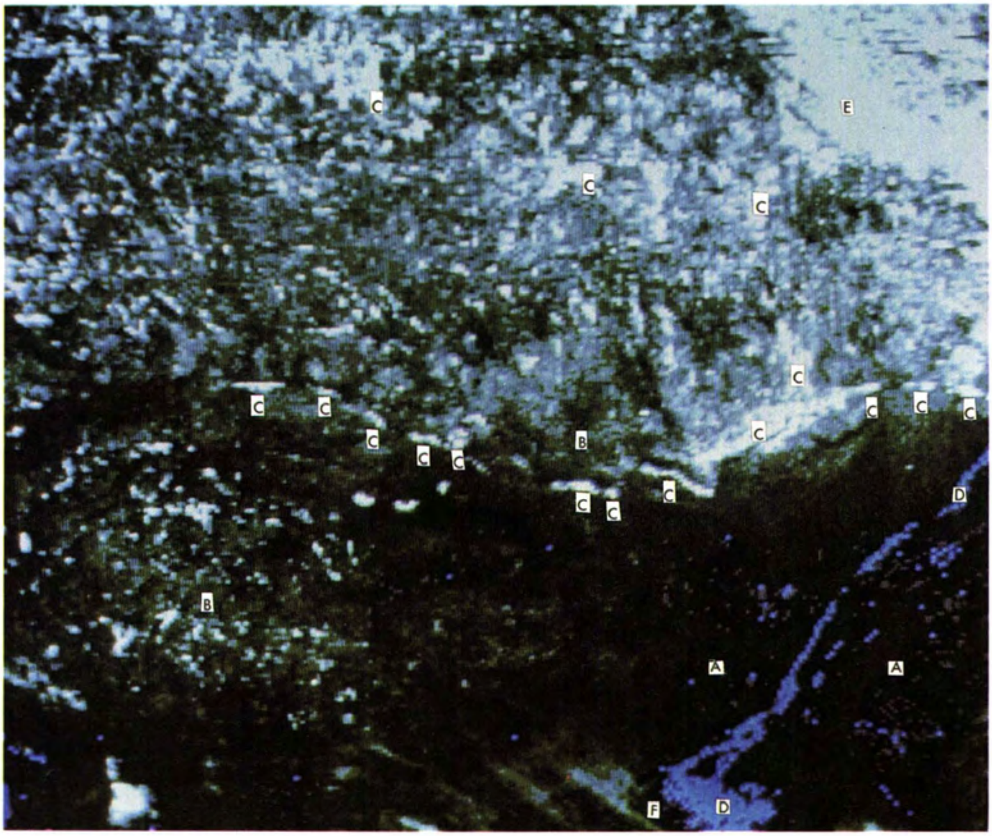

PLATE 1. Color-enhanced 2-km averaged image of Ottawa river basin created on MMIPS using VHRR digital data from 4/5/76.

of the image are also white (*E*). The ice-covered reaches of the Ottawa River (*C*) thus stand out from the surrounding forests, making interpretation of the imagery an easier task.

Enhancement through the use of colors does not always create a unique theme for identification of a particular feature such as river ice. In Plate 1, the thin cirrus near the eastern shore of Lake Ontario (*F*) have the same colors as both snow-covered and snow-free forests, light and dark green rather than white. However, an experienced image analyst would be able easily to detect and account for such obvious inconsistencies.

DISCUSSION AND FUTURE APPLICATIONS

Monitoring of changes in river ice from operational environmental satellites daily (clouds permitting) can be accomplished quickly and effectively by using the NOAA/VHRR visible data and optical devices such as the ZTS. Comparison of 1-km and 80-meter resolution images shows that, whereas significant detail is gained in using 80-meter resolution, the amount gained is insufficient to warrant sacrificing daily coverage by NOAA and GOES for once-every-18-day coverage by Landsat. The distortion observed in geostationary satellite imagery limits its usefulness to latitudes equatorward of 50° and so precludes monitoring many subarctic rivers where ice is a problem. The use of computers to locate and identify river ice is a possibility, one that could lead to a truly operational assessment of river ice.

During the melt season, many ice-covered rivers suffer from the problems of moving ice, which creates havoc with turbine intakes and ship navigation. Resulting ice jams also can cause flooding by back water build-up upstream from the jams with attendant property losses and displacement of individuals. Imagery from operational environmental satellites could be used to create an early warning monitoring system and thus reduce hardships and monetary losses.

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